Experiences with the practical application of Sweep Frequency Response Analysis (SFRA) on power transformers

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Abstract: Sweep Frequency Response Analysis (SFRA) has turned out to be a powerful and sensitive method to evaluate the mechanical integrity of core, windings and clamping structures within power transformers by measuring their electrical transfer functions over a wide frequency range. The contribution summarizes various aspects of the practical application of SFRA. After a short introduction of SFRA basics a survey of existing standards and guides on FRA is given. The different sources of reference data and their significance are discussed. Uncertainties are shown and tips for dealing with them are presented. The choice of test types is discussed for measurements without existing reference data. Information about the handling of test data is mentioned. Finally a summary of guidelines derived from a large number of successful measurements is given to put the reader in a position to achieve a good degree of repeatability, too.

1 INTRODUCTION

The deregulation of the electric power market involves increasing of economic pressure which requires a reduction in servicing and decreasing maintenance costs. On the other hand, we face aged and aging transformer fleets operating with increasing loads [1] all over the globe. Therefore, the diagnosis of this apparatus becomes more relevant in general but especially for strategically important or particularly risky transformers. In the last few years a fast-paced technical development regarding various aspects of measurements, data acquisition and analysis has taken place across the world. Sweep Frequency Response Analysis (SFRA) has turned out to be a powerful, non-destructive and sensitive method to evaluate the mechanical integrity of core, windings and clamping structures within power transformers by measuring the electrical transfer functions over a wide frequency range. This is usually done by injecting a low voltage signal of variable frequency into one terminal of a transformers winding and measuring the response signal on another terminal (see fig. 1). This is performed on all accessible windings following according guidelines. The comparison of input and output signals generates a frequency response which can be compared to reference data (see chapter 3).

The core-and-winding-assembly of power transformers can be seen as a complex electrical network of resistances, self-inductances, ground capacitances, coupling inductances and series capacitances as schematically shown in figure 2. The frequency response of such a network is unique and, therefore, it can be considered as a fingerprint.

Figure 1: Principle operation of SFRA

Figure 2: Network behaviour of a transformer’s active part (simplified)
Geometrical changes within and between the elements of the network cause deviations in its frequency response. Differences between an FRA fingerprint and the result of an actual measurement are an indication of positional or electrical variations of the internal components. Different failure modes affect different parts of the frequency range and can usually be discerned from each other. Practical experiences as well as scientific investigations show that currently no other diagnostic test method can deliver such a wide range of reliable information about the mechanical status of a transformer's active part.

2 STANDARDS AND GUIDELINES

The first mandatory standard in the world was established on 2005-06-01 in China. It is centrally managed by the Technology Commission for Electric Power Industry & High Voltage Test Technology Standardization and was developed through the cooperation of six national power engineering institutes. This standard, named DL 911/2004, only refers to SFRA measurements, suggesting that IFRA (Impulse-FRA) measurements are uncommon in China. It covers subjects including the test principle, requirements for testing instruments, testing methods and the analysis of the results. The standard mentions open circuit end-to-end measurements only and for the sense of measurements on star connected windings the standard requires the injection of the signal into the neutral terminal and a measurement of the response at the phase terminal. In two appendices, various test examples are given. The standard evaluates a frequency range between 1 kHz and 1 MHz and is unique in that it gives a mathematical rule about how to judge test results based on a calculation of co-variances [2].

In the following, two examples are given to show the application of this assessment. First, the outer HV phases of a 36-year-old transformer (40 MVA) after a refurbishment are compared (fig. 3). Both traces show good congruity which is in alignment with the known condition of the windings. The assessment according to the Chinese standard confirms this evaluation (green).

The second example shows HV winding test results (middle phase) of two 63-MVA sister transformers. One transformer has failed a dielectric test. The reason for this turned out to be shorted turns, which are clearly visible on an SFRA measurement and confirmed by the Chinese assessment (red - indicating a severe problem).

In 2002 the IEEE established a Task Force (TF) concerned with FRA and followed it up with a Working Group (WG) founded in 2004. The scope of this WG, termed PC 57.149, is the creation of a guide for the application and interpretation of FRA for oil immersed transformers. As usual for IEEE WG the members represent a balance between transformer manufacturers, utilities and third parties including consultants, testing companies and test instrument manufactures. The current draft contains a detailed definition section, an FRA overview with applications and a recommendation about the test parameters. A second part describes test procedures and gives tables of test connections for the most common transformer types. The content of test records is given and in a final section including case studies the analysis and interpretation of the test results is dealt with. In an appendix, FRA theory is shown in more detail.

As with the Chinese Standard, the IEEE will recommend a three lead test system for “source”, “reference” and “measurement”. This is in accordance with common scientific knowledge and is supported by all SFRA test instrument manufacturers. The IEEE draft guide proposes additional tests to those recommended by DL 911/2004. The IEEE draft guide also gives assistance by providing a mathematically-based trace assessment with cross-correlation coefficients, although it should be noted that it is not planned to recommend limiting values as are found in DL 911/2004.

The IEEE guide to FRA testing of power transformers may be published at the end of 2010 and will be a step forward for existing and prospective users of this technique. More information about this work can be found on the transformers committee homepage:
http://www.transformerscommittee.org/
The Cigré Study Committee (SC) A2 – Transformers - decided in 2003 to establish a Working Group on the application of FRA to power transformers. This WG A2/26 with the title “Mechanical Condition Assessment of Transformer Windings using Frequency Response Analysis (FRA)” started its work in 2004 and ended with the publication of Cigré report No 342 [3] in April 2008. During this period, besides regular meetings the WG organized two FRA test workshops. During these workshops a large number of practical investigations were performed. The main results and conclusions from the comparative testing were as follows: All test equipment produced essentially the same measured responses for the test objects over a mid-range of frequencies from about 10 kHz to 500 kHz. The impulse methods (IFRA) were unable to reproduce the low frequency response because of digitizers set to acquire only the higher frequencies. Some swept frequency methods also did not have sufficient dynamic range to reproduce the typical 90 dB minimum obtained with a 50 Ohms measuring impedance [4]. Figure 5 and 6 illustrate an important finding of the workshops. Figure 5 shows nine measurements, carried out at one bushing of a 400 kV transformer with one test instrument but using different cabling practices. Above 500 kHz intensive deviations show the significant influence of the connections.

Figure 5: Test results obtained with various cabling practices at the same 400-kV-bushing during a Cigré workshop [4]

After the standardization of good cabling practice was agreed by the WG-members, it was possible to get perfectly reproducible results at the same bushing up to approximately 1.5 MHz even with different test instruments (Fig. 6), which is sufficient for a reliable condition assessment. Finally, the WG worked out the best practice to take full advantage of the proven sensitivity of FRA for condition assessment of power transformers. The resulting brochure is a valuable source of information and a helpful guide for the practical application of FRA. More information about this work is available at the Cigré A2 homepage: http://www.cigre-a2.org/

Finally the IEC plans to establish a working group in 2009 to develop a standard for FRA testing until 2011.

3 PRACTICAL ASPECTS OF SFRA TESTING

SFRA is a comparative measurement method. This means results of an actual test – usually a set of curves (mainly the amplitude in dB’s over the frequency) representing all windings of a transformer as separate as possible – are compared to reference or baseline data. Three methods are commonly used to assess the measured traces:

1. Time-based (current FRA results will be compared to previous results of the same unit)
2. Type-based (FRA of one transformer will be compared to another of the same design)
3. Phase comparison (FRA results of one phase will be compared to the results of the other phases of the same transformer)

Thus, the first step before a measurement is to answer the question: Is reference data available? If FRA measurements have been performed on this transformer in the past, the results of the measurements should be uploaded into the software of the available FRA instrument and shall be analysed prior to the planned test. During this, one should check the existing data for consistency and correct documentation. A key factor of the documentation is the way the connections have been carried out. From a practical point of view it has turned out to be best practice to store photographs of the connection details together with the measurement data. This is significant help to achieve the highest possible degree of repeatability while reproducing the same arrangement for the measurement.
If the data is of reliable quality their analysis allows the tester to get an idea of the "expected results" which is vital for avoiding measurement mistakes. For the planned test the same measurements under the same conditions (e.g. tap changer position) have to be foreseen. According to the reason of the actual test additional measurements might be recommendable because different types of SFRA measurements are best-suited for different investigations. These decisions shall clearly be made before the start of the measurements since time pressure usually is one of the most common circumstances during transformer tests. Figure 7 shows an example of a time-based comparison on an 8 MVA-transformer (always HV phase 3). The black curve has been measured in 04/2006 the red curve in 5/2007 while the blue curve dates from 11/2008.

The core region below 1 kHz shows deviations due to different stages of core remanence which is natural. For the frequencies between 1 kHz and 1.5 MHz the tests have good congruity which is an indication for an unchanged geometry inside the transformer and thus the healthy status of the tested winding, considering the first test was performed on the phase being in healthy status, too. This has been the case for this transformer.

If no historical data of the concerning transformer is available, the use of SFRA data from type-equal ("sister-") transformers is common and mostly useful. The handling of the data is generally the same as described for the time-based comparison. However, minor deviations between curves of sister transformers can normally not be excluded. Figures 8 and 9 (zoomed) present an example of a successful type-based comparison of two 30-MVA transformers. Overlaying the data of the HV windings it is obvious that the related curves (same colours for each phase) correspond very well. Considering that it is most unlikely to have two transformers with exactly the same kind of mechanical failure, the good congruity of the results is a good indication for the healthy status of both units.

However, it is important to recognize that equally specified transformers not in every case show exactly the same frequency responses. An example for different SFRA results on identically specified 60-MVA single phase generator step-up transformers is given in figure 10. Despite the fact that all units were in good shape the SFRA results are not in alignment.

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Figure 11 shows a zoomed region of incongruity in a frequency range from 5 kHz to 550 kHz. Obviously the windings design has been changed during the manufacturing process of this batch of transformers. This assumption has been confirmed by the manufacturer.

![Figure 11: Zoomed view of the results shown in figure 10](image1)

The case above shows that a mismatch of SFRA results during a type-based comparison means not necessarily that one or both of the transformers are damaged. In such cases it is recommendable to use more than one reference test if available or to consult the transformers manufacturer.

If no reference data is available the set of tests shall be planned according international guides and with respect to the objectives of the test (fingerprint, failure investigation, transportation assessment etc.). The most common measurement is the end-to-end test with all untested terminals left floating. These curves contain the most informational content about the core and the winding and are therefore the most important kind of tests. Figure 12 shows the principle of this kind of test. In this case the signal source and the reference measurement channel are connected to the neutral terminal while the response measurement channel is connected to one of the star connected phases. It is also possible to use the opposite direction (signal injection in the phase and measurement on the neutral) but both directions should not be mixed.

![Figure 12: Principle of end-to-end tests with open circuit](image2)

Other tests can be the capacitive inter-winding test (fig. 13), end-to-end tests with a short circuit connection of the corresponding windings or the not that common inductive inter-winding test. Capacitive inter-winding measurements seem to be promising due to their high sensitivity in the detection of radial deformations. Anyway, the selection of the type of tests to be performed is also a matter of the available testing time. For the definition of the sweep settings it has been proven that a frequency range between 20 Hz and 2 MHz is usually sufficient. With respect to the further use of the actual data as references for future measurements it must be mentioned again that exact documentation is essential for SFRA measurements.

Without reference data it is common practice to compare the phases of a transformer against each other. For three-phase transformers it must be noted that the middle limb usually differs from the outer phases in the core region (up to a view kHz) as well as in higher frequency regions which are related to the winding structure under test. As an example figure 14 shows the HV winding responses of a 350-MVA GSU. It is visible that the middle phase (green curve) deviates slightly from the other phases (black and red).

![Figure 13: Principle of capacitive inter-winding tests](image3)

![Figure 14: Phase comparison of HV windings in healthy state](image4)

Despite this it is obvious that the resonances and anti-resonances are in good alignment which is a good indication of the healthy status of the windings. According to the authors experience app. 60% of all SFRA tests can be assessed just based on phase
comparisons. But it must be noted that also healthy windings may not correlate well, according to their winding design. In such cases further investigation (e.g. type-based comparison) is required. It can be estimated that app. 90 % of all SFRA measurements can be evaluated without fingerprint data of the tested object being available. In figure 15 an example of a newly build 63-MVA transformer is given. The HV windings show different winding responses despite being verifiable in sound condition. More often then for HV windings this kind of effect is to be observed on LV or tertiary windings.

4 RULES FOR REPEATABILITY

Finally a summary of guidelines derived from a large number of successful measurements is given to put the reader in a position to achieve a good degree of repeatability, too. This is of need because all types of assessments explained in chapter 3 are based on the ability to exactly reproduce the measurement results under same conditions. Without this it is often very critical or even impossible to distinguish between measurement mistakes and real damage inside the tested transformer.

- All connections from the transformer except the tank ground shall be removed.
- The contacts of the bushings shall be cleaned and the connection clamps have to be tightened firmly to assure reliable electrical contact.
- Three shielded high frequency cables (usually coaxial cables) of exactly same length should be used.
- It must be assured that the ground extensions of the measuring cable shields do not have electrical contact with the terminal contacts.
- Ground extension of the test leads must be of low inductance (broad braids with large surface, made of a large number of small wires to reduce the skin effect at higher frequencies).
- Ground extension to the base of the bushing (reference potential is the transformer tank) shall be as short as possible and with the smallest achievable loop.
- It is very important to ensure reliable contact between ground extension and tank. A lot of measurement mistakes are related to this point.
- Detailed information about the test set-up should be stored together with the test data. This will help to reproduce the measurements for future tests. Detailed photographs are recommended.
- Every test result should immediately be checked for plausibility and compared to expectations and available references. A very noisy curve is almost an indication for poor grounding. It is important to recognize measurement mistakes on-site and to repeat the questionable test after finishing the required corrections.

5 CONCLUSIONS & ACKNOWLEDGEMENT

The SFRA is a powerful method for the detection and diagnosis of defects in the active part of power transformers. It can deliver valuable information about the mechanical as well as the electrical condition of core, windings, internal connections and contacts. No other single test method for the condition assessment of power transformers can deliver such a diversity of information. Therefore the SFRA is an increasingly popular test. The value of fingerprint data is more and more recognized by users all over the world. Reproducibility is the key for a successful application of SFRA. Therefore highest accurateness is essential when establishing the connections. Comparing the time and the frequency domain FRA test methods is seems to be obvious that SFRA, measuring directly in frequency domain, prevailed. Due to the work of Cigré WG A2/26 consensus about the effective and reliable application of this method has been achieved. The authors wish to thank all members of this WG for their work.

6 REFERENCES